FLEXURAL CAPACITY OF OVERLOADING DAMAGED RC T-BEAMS STRENGTHENED WITH CFRP SUBJECTED TO WET-DRY CYCLES

Jianji Guang, Jun Deng*, Tonghua Liu and Yan Xie
School of Civil and Transportation Engineering, Guangdong University of Technology,
100 Waihuan Xi Road, University City, Guangzhou, China 510006.

ABSTRACT

Overweight trucks are common on the highways in China, which presents fatigue damage problem for the reinforced concrete (RC) bridges. Externally bonding CFRP sheets is increasingly being used to repair the damaged bridges. The degradation of adhesive bonding in a wet-dry environment, however, may have a significant adverse effect on the long term durability of the repaired bridges. This paper presents an experimental study on the flexural capacity of damaged RC T-beams strengthened with CFRP sheets subjected to the wet-dry cycles. A total of 19 specimens in 8 series were tested. The specimens were damaged by constant fatigue loading which were equivalent to the repetitive loadings caused by the overweight trucks across a bridge in one year. The specimens subjected to wet-dry environment were exposed to a period of 3 months or 6 months. A wet-dry cycle was 24 h including a wet cycle (salt water) of 10 h and a dry cycle (hot air at 40 ℃) of 14 h. The experimental results showed that a slight reduction in stiffness was observed for the strengthened beams due to overloading damage or wet-dry exposure. The residual deflection and cracks caused by overloading damage reduced the effect of CFRP strengthening. The wet-dry cycles induced degradation to bond at the concrete/FRP interface. Only in the first 3 months, however, the wet-dry environmental exposure can obvious reduce the strength of the retrofitted beams.

KEYWORDS

Flexural capacity, RC beams, fatigue overloading, wet-dry cycles.

INTRODUCTION

Reinforced concrete (RC) bridges in highway are subjected to an increasingly heavy traffic. Depending on the type of highway, components in decks can experience up to 7×10^8 stress cycles (Mays and Tilly 1982). Consequently, fatigue damage, especially caused by the overweight trucks, is one of the main problems that occur in highway bridges. Externally bonding carbon fibre reinforced polymer (CFRP) sheets to the tension face has been accomplished to repair the damaged bridges (Hollaway and Head 2001). However, the degradation of adhesive bonding in a hygrothermal environment may have an adverse effect on the mechanical behaviour of the repaired bridges. Therefore, specific research is needed to understand the durability of the repaired bridges under the environmental conditions.

To study the problem of the overload of vehicles, Yu et al. (2013) proposed a real-time overload monitoring system of bridges and roads based on the structural response. Ye et al. (2012) developed a stress spectra for fatigue life assessment of steel bridges with use of long-term monitoring data dynamic strain. The predicted fatigue life of Tsing Ma Bridge is varying slightly when using more than 10 daily strain data and keep almost the same when using more than 20 daily strain data. A damage model for the determination of damage caused by traffic was developed and applied on three RC bridges (Pircher et al. 2013). The results show that heavy trucks can cause high damage for all three bridges. Zhu (2011) developed an *S-N* curve of RC T-beams to predict the residual service life of highway RC simply-supported girder bridges. In addition, an *S-N* curve was developed from the test results to predict the fatigue life of the steel beams reinforced with CFRP plate (Deng and Lee 2009).

Choo el al. (2007) presents a study on a CFRP retrofitted RC bridge subjected to extreme vehicular loads. The increase in flexural capacity provides an adequate margin of safety against further overloading. The capacity and rigidity of the RC beams damaged by static loading were highly enhanced by CFRP strengthening (Benjeddou et al. 2007). The durability of RC beams reinforced with GFRP laminates were investigated by Almusllam (2006). The test results showed that none of the environmental conditions have a noticeable influence on the flexural strength of the retrofitted beams. The experimental tests on the durability of the concrete elements strengthened with near surface mounted CFRP laminates showed a decrease of around a 12% in the maximum pull-out force due to the wet-dry cycles (Garzon-Roca et al. 2015).

From above, the previous research has shown that heavy trucks may cause high damage in the RC bridges and CFRP externally bonding technique can restore their capacity. The influence of the wet-dry environmental exposure on the retrofitted RC members had investigated as well. However, the knowledge on the combined effects of overweight truck damage and wet-dry exposure on the retrofitted RC bridges is absent. In this paper, an experimental study on overloading damaged RC T-beams strengthened with CFRP sheets subjected to wet-dry environmental exposure was conducted. A total of 19 specimens in 8 series were tested. Fatigue loading cycles to damage the beams was equivalent to the repetitive loadings caused by the overweight trucks across a bridge in one year. The retrofitted beams were subjected to salt environments in a wet/dry environmental chamber for 3 or 6 months.

VEHICLE OVERLOADING SPECTRA

A weigh-in-motion system was installed on a simply-supported RC T-girder bridge of Guangzhou Round City Highway which is a typical highway bridge in south China. The weight of every vehicle across this bridge was recorded. The maximum stresses and stress ranges of the tensile longitudinal steel bars in the main girders were obtained based on the recorded vehicle weigh-in-motion and finite element analysis using MIDAS/Civil (2010). The rainflow cycle counting technique was used to transfer the complex irregular stress time histories into a set of constant stress range frequency data, which is listed in Table 1. The AASHTO (2002) allowable service moment is based on 60% of yielding stress of the steel bar which is 310 MPa in Chinese bridge standard (JTG D60-2004). Therefore, only the trucks with more than 100% allowed weight were considered in Table 1, of which the corresponding stresses of the steel bars were 173.7 MPa. In Table 1, the specified number of cycles per month for the *i*th overload rate or stress range was the average values in three typical months.

To calculate the number of cycles to failure for the *i*th stress range, an *S-N* curve for RC T-beams (Zhu 2011) was adapted, which is expressed as:

$$logN = 12.9047 - 3.2402 log\Delta\sigma \tag{1}$$

The methods of fatigue design and assessment are based on the Miner's rule for fatigue damage accumulation, which is expressed by

$$D = \sum_{i=1}^{k} D_i = \sum_{i=1}^{k} n_i / N_i \tag{2}$$

where D is the fatigue damage accumulation index. From the above equation, the fatigue damage accumulation indexes D_i was obtained and recorded in Table 1.

Table 1 Vehicle overloading spectra

Overloading rate /%	100-110	110-120	120-130	130-140	140-150	150-200	200-250	250-300
Max. stress /MPa	173.7	179.3	185.0	190.7	196.3	202.0	230.4	258.7
Stress range /MPa	113.4	119.0	124.7	130.4	136.0	141.7	170.1	198.4
Number of cycles n_i /cycles	167	110	80	56	42	79	16	2
Fatigue life N_i /10^4 cycles	168	151	128	113	98	85	47	29
Fatigue damage accumulation index D_i /10^{-4}	1.0	0.7	0.6	0.5	0.4	0.9	0.3	0.1

EXPERIMENTAL STUDY

A total of 19 specimens distributed in eight series were tested, containing each series one, two or three specimens. Table 2 summarizes the experimental program carried out. All specimens belonging to one series had equal characteristics. The series 'C' indicates control specimens. The references 'D', 'F' and 'H' indicate damage status, strengthening status and wet-dry environmental exposure status, respectively. The suffixed digital 3 and 6 indicate months of wet-dry environmental exposure.

Table 2 Experimental program and results

Series	Damage status	Strengthening status	Age at testing (months)	Number of specimens	Ultimate Loads (kN)	Ultimate Displacement （mm）
C	/	/	/	3	86.02	54.70
D	damaged	/	/	2	89.67	62.56
F	/	strengthened	/	3	159.73	43.69
DF	damaged	strengthened	/	4	155.40	43.28
FH-3	/	strengthened	3	1	146.31	44.76
FH-6	/	strengthened	6	1	149.98	39.25
DFH-3	damaged	strengthened	3	2	149.25	41.90
DFH-6	damaged	strengthened	6	3	154.91	42.30

Specimen

All beams had a T cross-section as shown in Figure 1, reinforced with 2 Φ14 mm steel bars. They are provided with Φ 6 mm diameter steel stirrups at 100 mm center to center spacing and distributed over the span. The mix proportions used to cast all beams were 1:1.81:2.77:4.51 (water: cement: sand: aggregate). The average 28-day compressive strength of the concrete was 36.62 MPa. The yield and ultimate stresses of steel bars were 397 MPa and 535 MPa, respectively, with an elastic modulus of 202 GPa. The CFRP sheet (UT70-30) used was a uni-directional CFRP supplied by Toray Industries. The ultimate strength and the elastic modulus of the CFRP were 3878 MPa and 244 GPa, respectively. The adhesive used was Lica-100 A/B, a two-part thixotropic epoxy resin. It had a modulus of elasticity of 3.2 GPa and a tensile strength of 55.5 MPa. All beams were cast from the same batch in the laboratory and then cured for 28 days.

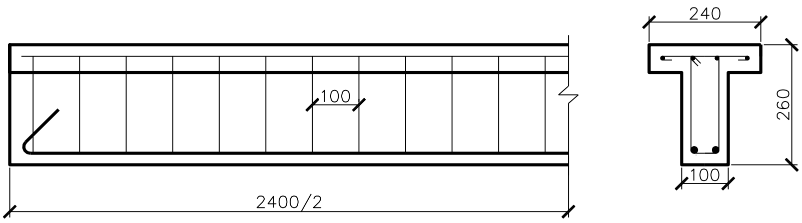

Figure 1 The beam cross-section (mm)

Preparation of strengthened specimens

The specimen series DF, DFH-3 and DFH-6 were overloading fatigue damaged before CFRP strengthening. The tensile concrete surface of each strengthened specimens was ground by a concrete scabbler until exposure of aggregate was achieved, then blown with clean air to remove dust and cleaned by acetone to ensure a good bond between the concrete surface and adhesive. After mixing, the adhesive was applied on to the beam and CFRP sheet. The excess adhesive was squeezed out along the edges of the sheet, assuming complete adhesive coverage. Two layers of CFRP sheet was bonded to the tension face of the strengthened specimens. In order to avoid CFRP sheet debonding at the ends during the testing, they were attached in three U-shapes with 50 mm extension on each side of the beams, as shown in Figure 2.

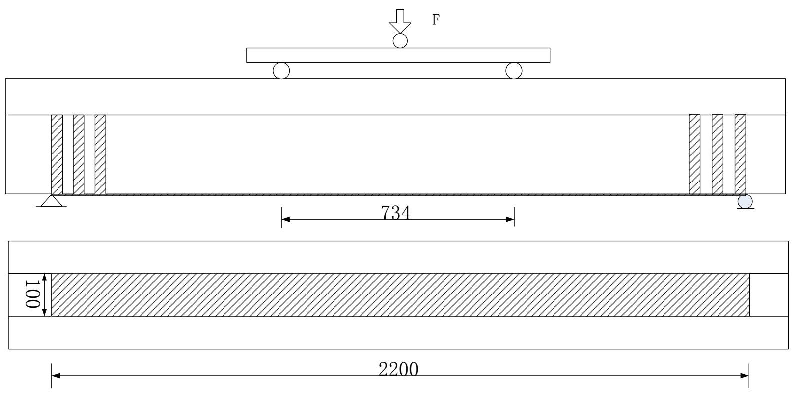

Figure 2 The strengthened beams (mm)

Wet-dry environmental exposure

The wet/dry environmental chamber has a length of 3 m, a width of 2 m and a depth of 1.5 m. The temperature control accuracy is ±1℃. The specimens were subjected to salt environments in which there were alternating wet and dry cycles. Sea water was simulated using 35 g of salt in 1 L of water which is equivalent to the average salinity of the oceans. The temperature of the hot air is 40 ℃. A wet-dry cycle was 24 h including a wet cycle of 10 h and a dry cycle of 14 h. The specimen series FH-3, FDH-3 and FH-6, FDH-6 were exposed for a total of 3 months and 6 months, respectively.

Test set-up and procedures

The tests were carried out in a servo-hydraulic SDS500 test machine with a maximum capacity of 500 kN, subjected to a four-point bending set up as shown in Figure 2. For retrofitted beams, the strain in the middle of the CFRP sheet was measured using two 20 mm long strain gauges. Deflections were measured at middle of the specimens using a potentiometer. All data were automatically recorded by a data logging system (TDS-530). The crack width was observed by a microscope. During loading, the strains, displacements and load were recorded every 1 second.

The specimens were damaged under fatigue loading. Loading was applied sinusoidally, with a frequency of 0.2 Hz. The minimum and maximum cycle loads are 16.8 kN and 73 kN, which convert to stresses σ of 60.3 MPa to 358.0 MPa. The minimum cycle stress 60.3 MPa was determined by the stress of longitudinal steel bars in the bridge main girders under self-weight and secondary permanent load. The maximum cycle stress 358.0 MPa was equal to the 0.9 time of the yield stress of the steel bar 397 MPa. According to Eq. (1), the corresponding number of fatigue cycles N was 69000. From the fatigue damage accumulation indexes in Table 1 and Eq. (2), the fatigue damage accumulation index for the T-girder per year is 55.2×10^{-4} and thereby the number of cycles in the tests is 380.

All specimens were finally tested under static load, by displacement control at a rate of 0.05 mm/sec. Loading was stopped when compressive concrete was crushed in the un-retrofitted specimens or when the CFRP sheet was tensile ruptured in retrofitted specimens.

EXPERIMENTAL RESULTS AND DISCUSSION

A summary of the test results including the ultimate strengths with their associated deflections, and the strain in CFRP sheets are given in Table 2. The un-strengthened beams in series C and D were failed due to compressive concrete crushed. The strengthened beams in other series were failed due to CFRP sheet ruptured.

Fatigue overloading damage

The damage in the RC beams was cumulated with the cyclic overloading. The average deflections at middle of the beams in series D, DF, DFH with the number of cycles were shown in Figure 3. The average curves were used instead of all curves to avoid cumbersome presentation. The figure shows that the deflections increased quickly in the first 60 cycles and varied slightly in the rest cycles. The damage of the specimens was identified by residual deflection and cracks, as shown in Table 3. The average residual deflections of the beams were 0.91, 1.47, 1.11 mm, respectively, which indicates that the fatigue overloading damage weakened the stiffness of the beams. The width of the residual cracks in part of beams was more than 0.2 mm which is the allowed width of cracks in RC beams in Chinese bridge standard (JTG D60-2004). This indicates that these beams need be repaired after one year fatigue overloading damage.

Table 3 The results of overload damage tests

Series	Residual crack width （mm）	Residual deflection （mm）
D	0.11	0.91
DF	0.28	1.47
DFH	0.26	1.11

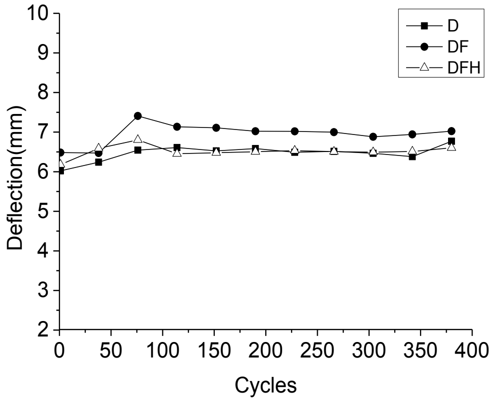

Figure 3 Deflections during the fatigue cycles

Flexural Capacity

All specimens were statically tested to determine ultimate strength and deflections. The test results in the form of load-deflection behaviour are presented in Figure 4. Average curves of each series were used to instead of the curves of all specimens to avoid cumbersome presentation. Two aspects are noted from Figure 4. Firstly, all the strengthened beams showed a strength enhancement over the un-strengthened beams, but the strengthened beams have very little enhancement in stiffness prior to the un-strengthened beams yielding. Secondly, the overloading fatigue damage and wet-dry exposure have only marginally effects on the load-deflection curves.

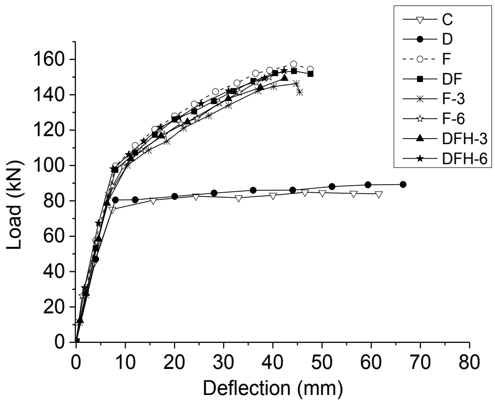

Figure 4 Load-deflection curves

The average ultimate loads and deflections of every series were recorded in Table 2. The comparisons of the average ultimate loads are shown in Figure 5 as well. As shown in the table, the damaged RC beams in series D have a higher strength and lower stiffness than the control beams in series C. This is because that the cyclic overloading increased the strength of the longitudinal steel bar by the effect of cold draw but damaged the concrete. The CFRP strengthening increased the ultimate strength of the undamaged beams in series F by 85.7% and the damaged beams in series DF by 73.3% in comparison with series without CFRP C and D, respectively. It indicates that the CFRP strengthening has less effective for the damaged RC beams due to the residual deflection and cracks. Comparing the specimens in series F and DF, the 3 and 6 month wet-dry cycles reduced the ultimate strength of the strengthened RC beams in series FH-3 and DFH-3 by 6.0% and FH-6 and DFH-6 by 3.7%, respectively. The wet-dry environmental exposure has clearly effect on the mechanical behaviour of the CFRP reinforced concrete members for the first 3 month but this effect is marginal for the next 3 month and even longer period (Huang 2014). The strength of the concrete, meanwhile, increased with the time of immersing in the water. These explain that the strength of the specimens under the wet-dry environmental exposure reduced in the first 3 months and then slightly increased in the next 3 months.

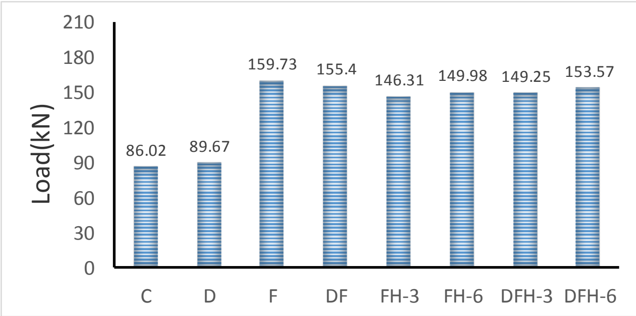

Figure 5 Ultimate loads

The strain in the CFRP sheet at the middle of the beams during the tests was presented in Figure 6, from which the following observation can be made: The specimens had a linear behaviour up to the yielding of the beams. Large deformation occurred and the strains increased rapidly in strain gauge after the beams had yielded. The specimens in all series but series F had the similar load-strain curves. The specimens F without damage and environmental exposure had a slightly smaller strain at the same loads than other specimens. It indicates that the retrofitted beams in series F had better stiffness than others, which can also be observed in Figure 4.

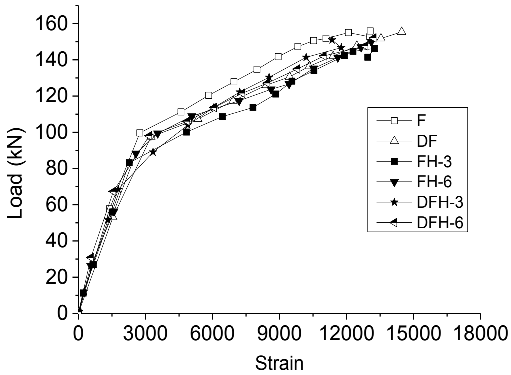

Figure 6 Load-strain curves

The width of the cracks in the middle of the specimens was measured at the load level of 79 kN. The average values of series C, F, DF and DFH-3 are 0.22 mm, 0.12 mm, 0.19 mm and 0.40 mm, respectively. The width of the cracks in the strengthened specimens in series F was about half of that in the control specimens in series C, which indicates the CFRP strengthening effectively restricts the crack opening. Due to the residual cracks caused by the fatigue overloading cycles, the strengthened damaged specimens in series DF have wider cracks than the specimens in series F. The width of the cracks in the specimens in series DFH-3 was about two times than specimens in DF. This is because that the degradation of the bond of FRP sheets with concrete after wet-dry exposure reduced the effect of CFRP strengthening, which was also the reason of the peak load reduction of the strengthened beams after wet-dry cycles.

CONCLUSIONS

This paper has presented an experimental study on overloading damaged RC T-beams strengthened with CFRP subjected to wet-dry environmental exposure. A total of 19 specimens in 8 series were tested. 4 series were damaged under fatigue loading cycles which are equivalent to the vehicle load caused by the overweight trucks on highway bridges during one year. 4 series were exposed under the wet-dry cycles for 3 or 6 months. The following conclusions can be drawn from the experimental results. (1) The residual deflections and cracks in the RC T-beams damaged by the fatigue overloading cycles cannot be ignored and the beams need be repaired. (2) A slight reduction in stiffness was observed for the strengthened beams due to overloading damage or wet-dry exposure. (3) The residual deflection and cracks caused by overloading damage reduced the effect of CFRP strengthenings. (4) The strength of the CFRP retrofitted specimens reduced 6.0% by 3 months wet-dry cycles but only 3.7% by 6 months wet-dry cycles. It indicates that the wet-dry environmental exposure has obvious effect on the strength of CFRP strengthened beams only in the first 3 months. (5) The degradation of the bond of FRP sheets with concrete after wet-dry exposure caused a significant increase of the crack width in the strengthened beams. (6) The pre-damage caused by the fatigue overloading cycles did not show a noticeable influence on the flexural properties of the specimens subjected to wet-dry cycles.

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